

# **Design of a high brightness beamline for protein crystallography at the ALS**

Howard Padmore, Feb. 2<sup>nd</sup> 1999

## **1. Introduction**

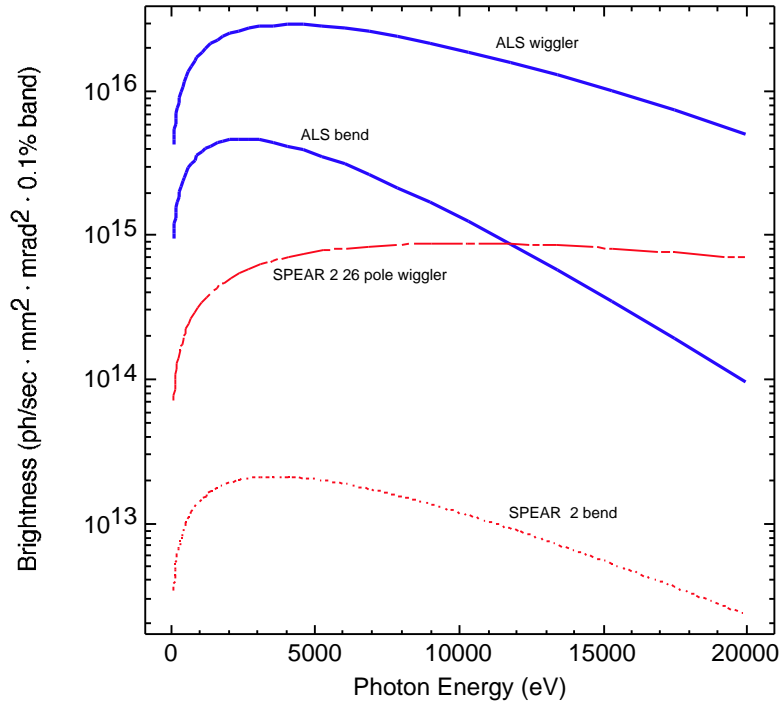
The high brightness of 3<sup>rd</sup> generation synchrotron radiation x-ray sources offers unique possibilities for protein crystallography. The combination of rapid tunability, extremely small beam sizes, and high beam stability means that structures can now be solved routinely and rapidly using the technique of Multiple wavelength Anomalous Diffraction (MAD), even on small crystals. Another frontier in this area is simply capacity, the need to measure many crystals, and is driven by the huge growth in the development of structural biology. This need can only be addressed if there are sufficient MAD beamlines available, and this in turn means that the costs of beamlines and detector systems have to be minimized. The extremely small beam size of the ALS bending magnet sources, together with advances in x-ray optics means that even with a relatively low power x-ray source, outstanding performance can be obtained at modest cost. We describe here the beamline optical design, the engineering layout, and the performance characteristics.

## **2. General considerations for protein crystallography on an ALS bending magnet source**

As many modern protein crystallography facilities are based on high power multipole wiggler sources, it is worth considering the merits of a low power bending magnet source.

Fig. 1 shows the brightness of an ALS center bending magnet under normal running conditions (1.9 GeV) in the 1 – 20 keV range, in comparison to a state of the art wiggler on a second generation source. It can be seen that for all energies less than 12 keV, the brightness of the ALS bend magnet is higher. At first sight this is difficult to understand as the energy of the second generation machine shown is higher (3 GeV), and the wiggler has 26 poles with a peak field of 2 Tesla, compared to an ALS bend magnet with 1 pole of 1.27 Tesla. The reason is that the low emittance of the ALS electron beam, combined with the small betatron function in the bend magnets leads to an extraordinarily small beam size. The beam size is only 24  $\mu\text{m}$  FWHM in the vertical plane, and 240  $\mu\text{m}$  FWHM in the horizontal plane, for the center bend magnet shown here. The area of the beam is approximately 70 times smaller in an ALS bend in comparison to the example taken of an SSRL wiggler straight, and this fully makes up for the 26 poles of this latest wiggler source at SSRL. It should also be noted that this brightness is achieved at minimal radiated power, whereas the wiggler source has to generate orders of magnitude more power. The ALS bend magnet is a low power, but high brightness source.

The great benefit of a low power, high brightness source is that as the complexity and cost of a beamline is strongly coupled to issues of cooling optical elements, masks, apertures etc, a low power source can be significantly less expensive than a high power beamline. In general, optics can be more sophisticated without the need for complex cooling schemes, and optical elements can be made to sufficient precision, and kept so under irradiation, that the focusing is near perfect. This is not generally the case in high power beamlines.



**Fig. 1** Brightness of an ALS center bend magnet for 1.9 GeV operation in comparison to other sources

The brightness of a source is only partially related to the figure of merit of a source for crystallography. For wiggler and bending magnet source, a parameter that approximately scales as the useful flux through a crystal is the horizontal brightness, averaged over the collection aperture. This average is necessary for wiggler sources as there is a correlation between the apparent horizontal source size, and the collection angle; as the wiggler is viewed at increasing off axis angles, the source appears larger due to its finite length. On axis, the wiggler also appears to be larger than the storage ring electron beam size due to the amplitude of the oscillation of the electron beam passing through the wiggler field. The vertical source size and divergence are so small in a 3<sup>rd</sup> generation synchrotron radiation source that the product of the electron beam size and the photon beam divergence, the source vertical phase space is always less than the size of a crystal and the required collimation to resolve adjacent diffraction orders. In second generation machines, the vertical phase space is sometimes larger than the acceptance of a crystal, and due to the restrictions of focusing, light is often lost even in the vertical direction.

The ALS has two types of bending magnets, the outer pair of magnets in the triple bend achromatic structure of the ALS lattice, and the center magnet. As the outer magnets have the smallest beam size they have the highest horizontal brightness, and so we propose to use one of these ports for the beamline presented here. For normal running conditions of the ALS at 1.9 GeV electron energy, the full width at half maximum (FWHM) of the electron beam size in one of the outer magnets is 106  $\mu\text{m}$  (v) by 127  $\mu\text{m}$  (h). The majority of crystals now being measured have dimensions of 100  $\mu\text{m}$  or less, and so it can be seen that if the ALS source can be focused efficiently to the crystal, the coupling through a collimator onto the sample will be very high. In comparison, in a 2<sup>nd</sup> generation wiggler source beamline, less than 1% of the light would be transmitted through the same sized aperture, even though the beamline would

have to be constructed to deal with the 99% that ends up being blocked by the sample collimator. In addition, the vertical angular divergence of the source is small, around 0.2 milliradians FWHM at 12 keV, and given that the required angular collimation at the crystal is always larger than 1 milliradian, we have the opportunity to demagnify by up to 5 without causing blurring of the diffraction pattern. Another advantage of the ALS lattice is that it is possible to get close to the source, unlike higher energy machines. The first optical element can be as close as 6 m from the source, offering the possibility of a large collection aperture, with small optical elements. The small length of the optics, together with the fact the required manufacturing tolerance decreases as the source – mirror distance decreases, means that it is relatively easy to preserve the source brightness, whereas in higher energy machines where the optics are usually a long way from the source and have to be larger, this becomes much more difficult.

The extremely small source size of the ALS bending magnet sources, together with the small distance possible between the 1<sup>st</sup> optical element and the source, means that we can have highly efficient beamlines that will significantly out-perform wiggler sources, but which are relatively inexpensive, and can be constructed rapidly.

### **3. Selection of the beamline design**

The traditional approach to building beamlines capable of focusing and rapid scanning has been to use an optical arrangement consisting of a tangential cylinder mirror to act as a vertical collimator, a non-dispersive 2 crystal monochromator using plane crystals, and astigmatic double focusing from a toroidal mirror. This arrangement has been used many times, including the ALS 5.0.2 wiggler beamline for protein crystallography [1]. While the focusing quality is adequate for the large optical source size of a wiggler, the optical aberrations of the astigmatic toroid are far too large for use with the small source size of an ALS bending magnet. We have therefore reviewed several competing designs that offer the necessary high quality focusing;

#### **a) 1:1 toroidal mirror imaging with a plane 2 crystal monochromator**

This approach has been taken in ALS beamline 7.3.3, where energy resolution was not of prime importance. A single toroid focuses from the source to the crystal sample at 1: 1 magnification. The light is monochromatized by a single channel cut Ge[111] crystal, approximately 1.5 m from the focus. The system is simple, but this has the severe problem that the energy resolution is limited by the convergence of the light. For example, at full aperture, the resolving power is approximately 1000, and in some cases this will not be adequate for MAD studies. Of course the resolution could be improved by reduction in aperture, with a consequent reduction in flux.

#### **b) 1:1 toroidal mirror imaging with a gradient crystal monochromator**

The problem in a) can be entirely solved in an elegant way suggested by Erko [2], in which the divergence of the light is compensated by a commensurate change in the lattice spacing of the crystals in the monochromator. The small change is produced by growing a Ge doped crystal, in which the Ge concentration changes in a linear fashion along the crystal surface. In this way, even in a divergent beam, a single wavelength is diffracted. In this case the monochromator has to be placed before the toroid. From our experiences on beamline 7.3.3, we already know that toroidal mirrors can be made to

sufficient accuracy. However, the technology of making Ge doped Si is not as advanced as we would like, and more research in this area is needed. Erko has produced excellent results on relatively small crystals, and it is expected that this will soon be a viable technology. The intrinsic resolving power of Si[111] of 7000 at 12 keV would be realized with this design. A variant of this approach is to bend plane Si crystals in the tangential plane to compensate for divergence. In order to do this to the required accuracy is difficult, and combined with 1<sup>st</sup> crystal cooling would require significant R&D. However both of these approaches are attractive as future possibilities.

c) collimation and refocusing with toroidal mirrors combined with a plane 2 crystal monochromator

The problems of divergent light can be eliminated using a toroidal first mirror bent to focus at infinity, followed by a conventional plane 2 crystal monochromator, and a second toroidal mirror designed to focus from infinity to a point. Several of these types of monochromator have been built, but the optical aberrations of the toroidal approximation to a paraboloid, although much better than the conventional astigmatic toroid arrangement, are too large for this application. In addition, the generating axes of the two mirrors have to be precisely aligned to get the desired performance.

d) vertical collimating and refocusing mirrors with a sagittal focusing monochromator

A variation of c) above is to use tangential cylinder mirrors to collimate and re-focus in the vertical direction, together with horizontal focusing provided by a 2 crystal monochromator in which the 2<sup>nd</sup> crystal is sagittally bent. This concept, introduced many years ago by Sparkes et al [3], has been widely used in wide aperture monochromators. However it has only recently been used for high brightness applications. The sagittal curvature of the 2<sup>nd</sup> crystal is produced by bending, usually with equal end couples, on a crystal that is ribbed to prevent anticlastic bending. This design has been used at the Structural Biology “CAT” beamline BM 19 at the Advanced Photon Source, based on the design of Rosenbaum [4]. This design has achieved a 130  $\mu\text{m}$  (FWHM) horizontal focus on an APS bending magnet [5], and is capable of the Dawin width limited resolving power at 12 keV of 7000.

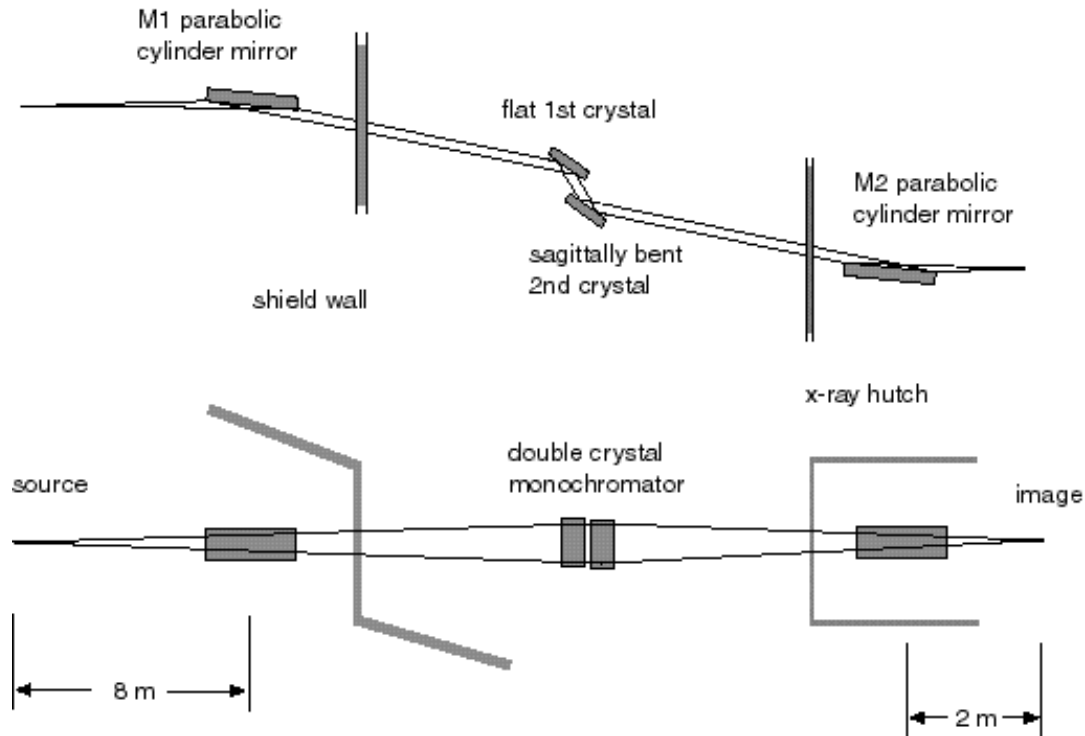
The designs presented above are not an exclusive list, but represent the major classifications of optical systems that are suitable for this application. There is no doubt that 2), the gradient crystal design will ultimately be the design of choice, but the proven performance of low aperture sagittal focusing for high brightness applications makes this the natural choice at this point. However, the development of gradient crystals is rapidly evolving, and we will work to assess the prospects for the use of this new optical element in the next few months. If this turns out to be a robust technology we will switch designs. The additional cost of the crystals, together with an additional stage of vertical micro-focusing that may be needed make the costs of the two systems very similar.

#### **4. Proposed beamline design**

The design is shown schematically in Fig. 2. At 8 m from the source, inside the shield wall of the storage ring, a parabolic mirror will focus light diverging in the vertical direction to produce a parallel beam. The light will continue to diverge in the horizontal direction until reaching the crystal monochromator. The monochromator will be a conventional double crystal non-dispersive design, with a flat 1<sup>st</sup> crystal, and a sagittally bent 2<sup>nd</sup> crystal to provide 1:1 horizontal focusing. The parallel beam in

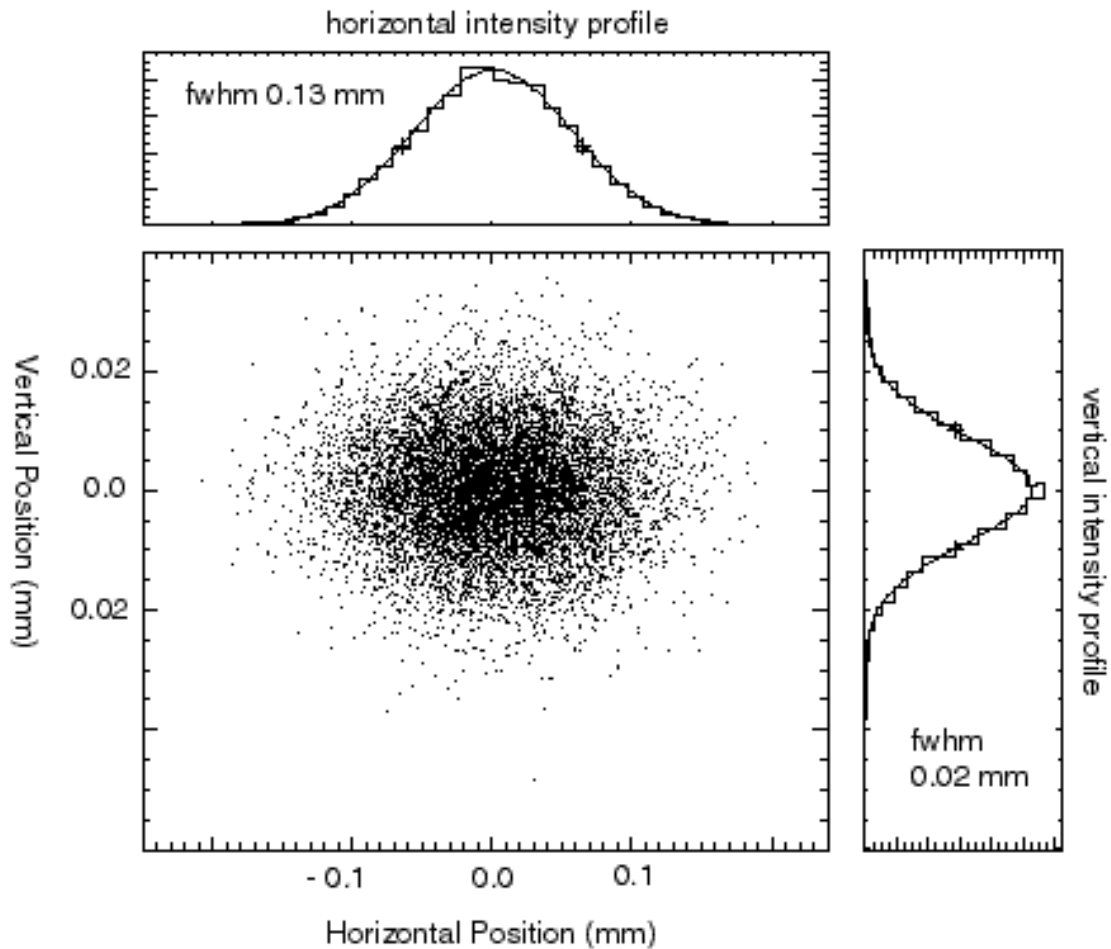
the vertical direction is then focused to the sample with a 2 m focal length parabolic mirror. This arrangement has the following features;

- a) the resolution is determined only by the 1<sup>st</sup> crystal
- b) the beam is demagnified in the vertical direction, giving a beam size of around 25  $\mu\text{m}$  FWHM with a convergence of 0.78 milliradians
- c) the sagittal focusing of the 2<sup>nd</sup> crystal provides an aberration free image, at the 3 milliradians acceptance used here
- d) the mild curvature of the sagittally bent 2<sup>nd</sup> crystal in comparison to the severe curvature of a toroidal mirror focusing system produces only a small image curvature away from the focus. This is important as the focus is at the crystal sample, and the detector is out of focus.
- e) the arrangement is flexible, with the source to sample distance a parameter that can be adjusted easily to suit the experimental area floor layout.
- f) putting the M1 mirror inside the shield wall means that to collect the full vertical aperture we can use relatively short M1 and M2 mirrors (0.5 m for 92% of the aperture at 12 keV). In addition, the slope error tolerance required to preserve brightness becomes reasonable, as it is directly related to the angular size of the source from a point on the M1 mirror.



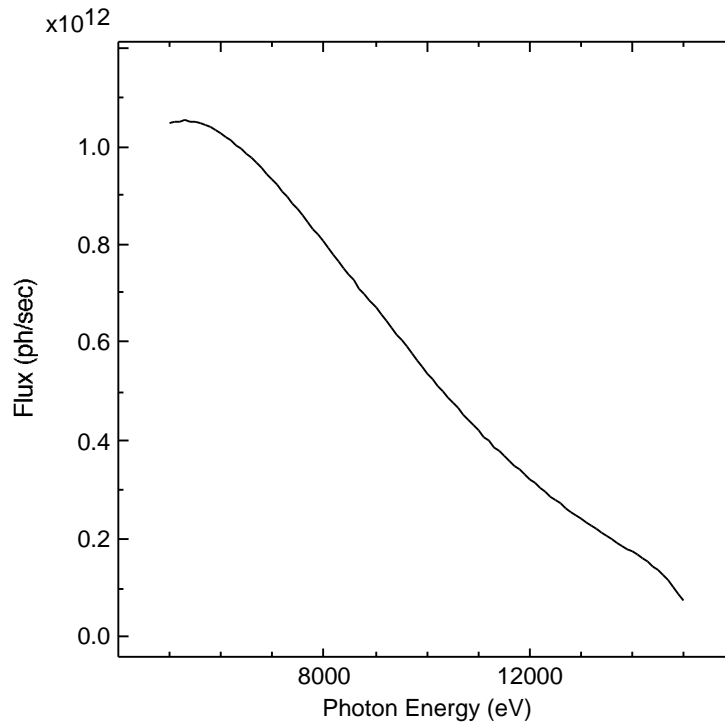
**Fig. 2** Optical layout of the proposed beamline

The original design of Sparkes et al [3] showed that in order to accept large horizontal apertures, the angular error between the 1<sup>st</sup> plane crystal and the second sagittally bent 2<sup>nd</sup> crystal were minimized when the system demagnified in the horizontal direction at 3:1. In this case however, this would mean that to maintain the angular convergence onto the sample at 3 milliradians, only 1 milliradian could be accepted from the source. While this would be fine for 30  $\mu\text{m}$  diameter crystals, for 100  $\mu\text{m}$  crystals the width would be underfilled and only 1/3 of the flux of a 1:1 system would be available. The restriction on magnification becomes important when accepting very large horizontal apertures; in general for the small horizontal aperture used here, there is a significant range of magnifications which give angular mismatches far less than the single crystal Darwin reflection range. For the 1:1 horizontal focusing geometry proposed here angular mismatch between the two crystals is small, and the throughput is only fractionally lower than the two plane crystal case.



**Fig. 3** Simulated focus of the proposed beamline

One of the features of this beamline configuration is that it allows for easy demagnification in the vertical direction. The vertical divergence of the light from an ALS bend magnet is 0.195 milliradians at 12 keV, and so here we demagnify by 4:1, giving a beam convergence at the sample of 0.78 milliradians. This is smaller than will be used on this beamline, even for very large unit cell crystals, and so we simply gain in flux density for small crystals. For larger crystals we will be able to defocus the beam by slight unbending of the parabolic refocusing mirror. Fig. 3 shows the expected image quality, obtained by simulation with the “Shadow” package. The vertical source size used for this simulation corresponded to the ALS running with half of the standard vertical emittance, hence giving a beam size of 70% of the standard. The current vertical emittance is  $1 \times 10^{-10}$  m · radians, but the machine has operated down to a factor of 3 lower than this value. The present value is set by adjustment of skew quadrupoles to couple horizontal emittance into the vertical plane, and is done to maintain an electron beam current halving time of 4 hrs (9 hour 1/e lifetime at the injection current of 200 mA). The electron beam lifetime is set by electron – electron scattering, the Touchek effect, and so can be reduced by increasing the electron beam dimensions. However, the addition of a 3<sup>rd</sup> harmonic bunch lengthening cavity in summer 1999 will give the opportunity to operate with a vertical emittance 3 times smaller, or 3 times longer lifetime, or a combination. Longer lifetimes are required, and so here we take half of the current vertical emittance to represent the lower limit of operations in the future. This gives an image size of 130 (h) by 20 (v)  $\mu$ m FWHM with an angular convergence of 3 by 0.78 milliradians.



**Fig. 4** Flux output of the proposed beamline.

The flux output of the beamline is shown in Fig. 4. The ALS running conditions used were the standard configuration of 1.9 GeV, 400 mA current, bend field of 1.27 Tesla, and a horizontal angular acceptance

of 3 milliradians. The beamline parameters used were M1 and M2 mirrors at 4.5 milliradians grazing angle with 5 Å rms surface roughness, rhodium coated, Si[111] double crystal integral reflectivity, and a single beryllium window of thickness 250 µm. The wavelength dependent fractional vertical acceptance of the mirror system was also included. The general slope towards higher energies is caused by the low critical energy of the ALS bending magnets, the plateau at 6 keV is caused by the onset of the beryllium window transmission, and the steeper gradient at 14 keV is caused by the onset of the reflectivity cut-off of the mirrors. The flux at the Se K edge, 12.6 keV, is  $2.6 \times 10^{11}$  ph/sec, in the bandpass of Si[111], 1.8 eV at this energy. This type of modelling was carried out for an existing ALS x-ray beamline recently, and essentially 100% agreement was obtained between experiment and simulation. We can be confident that near the predicted flux would be obtained in this case.

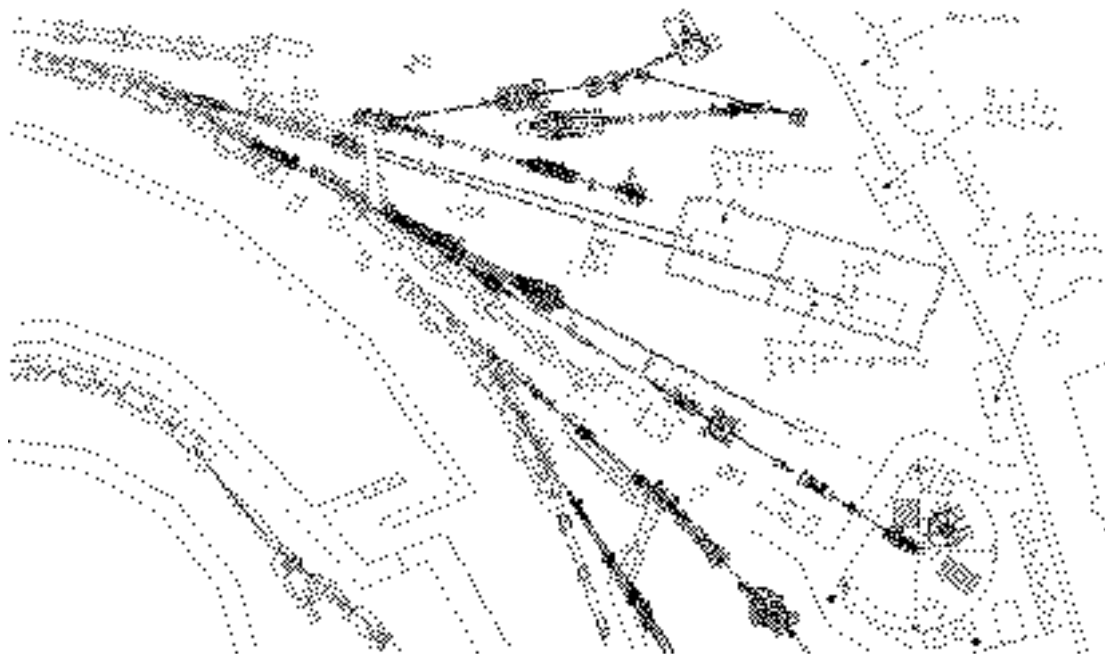
The fractional transmissions through a 100 µm collimator at the Se K edge will be 65%, giving a flux of  $1.7 \times 10^{11}$  ph/sec, or through a 30 µm aperture (with the present  $1 \times 10^{-10}$  m · radians vertical emittance) the flux will be  $4.5 \times 10^{10}$  ph/sec. These values are higher than most operating beamlines for protein crystallography today. We can calibrate how good this performance is by considering the radiation damage threshold [7,8,9]. The generally accepted value for the maximum integrated incident flux of 12 KeV photons that a protein crystal can intercept before substantial resolution is lost is  $10^{11}$  ph/µm<sup>2</sup>. This is really an upper estimate, and clearly at 2Å resolution substantial information is lost at this value. With the projected photon flux density calculated here, the time to accumulate this incident flux will be 26 minutes. This is about the same as the dead time of a modern CCD x-ray detector for 100 frames of data, and including time to mount and align crystals, it can be seen that the limited flux of an ALS bending magnet will not be a limiting factor in overall acquisition time.

## **5. Beamline layout and mechanical design.**

The layout is shown in Fig. 5. The beamline will be one of a pair of similar systems, one for protein crystallography, and one for powder diffraction.

The beamline consists of the 0.5 m long M1 parabolic mirror inside the shield wall at 8 m from the source, the monochromator at 10 m from the source, and a 0.5 m long M2 parabolic mirror at 28 m from the source, focusing with a focal length of 2 m to the crystal sample at 30 m. The M2 mirror would be located inside the end station x-ray hutch, in a high vacuum system, and the beamline would terminate in a thin beryllium window close to the collimator. In many cases it may be unnecessary to use a collimator due to the small size of the beam. The M2 mirror will be bendable, and the beam could be refocused for larger crystals if necessary. The monochromator will be a commercial 2 crystal monochromator, as used at BM 19 at the APS. This is a well understood and robust design. The parabolic mirrors would be bent from flats using the application of unequal end couples. These would be based on existing designs developed for micro-focusing at the ALS [10], and would use leaf springs to apply the couples [11]. The M1 mirror will be made from silicon, and will have side cooling via a GaInSn liquid metal interface. The total power absorbed by M1 of 2.61 W, and the low power density of  $5 \times 10^{-4}$  W/mm<sup>2</sup> means that a simple low cost cooling scheme can be used. The power absorbed by the 1<sup>st</sup> crystal of the monochromator will be 16.5 W, with a power density of 0.23 W/mm<sup>2</sup>. This can be dealt with by simple cooling of the upstream and downstream edges of the crystal block. The beryllium window will be upstream of the M1 mirror at 6.5 m from the source, and will absorb 24 W in a 20 mm wide line, with a peak power density of around 0.6 W/mm<sup>2</sup>. The control station will be adjacent to the

beamline, next to the walkway around the outside of the building. Due to the fact that only monochromatic light will be available in the hutch, and that there is not a high energy x-ray hazard, the hutch can be of a simple construction using 1/16 inch thick steel. As the first deflection is inside the shield wall, it means that a simple lead backstop can be used in the beamline outside the shield wall to stop the bremsstrahlung radiation, again simplifying the construction.



**Fig. 5** Layout of the proposed system on beamline 9.1.1

## 6. Summary

The 9.1.1 beamline for protein crystallography will combine collimating and focusing optics in the vertical direction, with a horizontally focusing 2 crystal monochromator. The expected beam size is around 130 (h) by 25 (v)  $\mu\text{m}$  with a convergence angle of 3 (h) by 0.78 (v) milliradians. The beamline construction is simple, and takes advantage of the extraordinarily high brightness of the ALS bending magnet sources to produce a very high flux density. It is expected that the radiation damage threshold will be reached in around 30 minutes when the beamline is used in its focused mode.

## References

- 1) A beamline for macromolecular crystallography at the ALS  
H. A. Padmore, T. Earnest, S-h Kim, A. C. Thompson and A. Robinson  
Rev. Sci. Instrum. **66** (1995) 1738
- 2) Graded X-ray Optics for Synchrotron Radiation Applications  
A. Erko, M. Veldkamp, W. Gudat, N. V. Abrosimov, S. N. Rossolenko, V. Shekhtman,  
S. Khasanov, V. Alex, S. Groth, W. Schroder, B. Vidal and A. Yakshin  
J. Synch. Rad. **5** (1998) 239
- 3) X-ray monochromator geometry for focusing synchrotron radiation above 10 keV  
C. J. Sparkes, B. S. Borie and J. B. Hastings  
Nuclear Instruments and Methods **172** (1980) 237
- 4) Sagittally focusing scanning monochromator produces 0.4 mm focus  
G. Rosenbaum, M. Sullivan, R. Fischetti and L. Rock  
Rev. Sci. Instrum. **63**(1) (1992) 931
- 5) Dr. E. Westbrook, Biology Department, Argonne National Laboratory; private communication.
- 6) Shadow; a system for raytracing x-ray optics  
B. Lai, K. Chapman, F. Cerrina,  
Nucl. Instrum. Meth. **A 266** (1988) 544
- 7) Cryo-protection of protein crystals against radiation damage in electron and x-ray diffraction  
R. Henderson, Proc. Roy. Soc. **B 241** (1990) 6-8
- 8) Cryo-protection of protein crystals in intense x-ray beams  
A. Gonzalez, A. W. Thompson and C. Nave, Rev. Sci. Instrum. **63**(1) (1992) 1177-1180
- 9) Radiation damage in protein crystallography  
C. Nave, Radiation Physics and Chemistry **45**(3) (1995) 483-490
- 10) Some new schemes for achieving high-accuracy elliptical x-ray mirrors by elastic bending.  
H. A. Padmore, M. R. Howells, S. Irick, T. Renner, R. Sandler, and Y-M Koo  
SPIE **2856**, pp 145-156 (1996), Optics for High Brightness Synchrotron Radiation Beamlines II,  
Denver, Aug. 1996

11) Design, analysis, and performance of an epoxy bonded bendable mirror  
N. D. Hartman, P. A. Heimann, A. A. MacDowell, K. D. Franck,  
A. P. Grieshop, S. C. Irick and H. A. Padmore  
SPIE (1998), Materials, manufacturing and measurement for synchrotron  
radiation mirrors, San Diego, Aug. 1998